IDENTIFICATION OF PLASTIC MATERIAL BEHAVIOUR OF THICK HIGH STRENGTH STEEL THROUGH FEMU TECHNIQUES

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1. INTRODUCTION

The use of thick High Strength Steels (HSS) in the pipeline industry increased noticeably in recent years. HSS pipeline constructions enable a lighter and slender structure without loss in strength. Unfortunately, the increase of the yield strength does not correspond with an increase in ductility; hence brittle fracture can occur in HSS pipeline constructions. Clearly, the latter is a serious treat with respect to public safety and the environment. A profound understanding of the plastic material behaviour of HSS is mandatory to ensure HSS pipeline integrity. To be specific, the plastic material response of thick HSS at large plastic strains is required to perform sufficiently accurate finite element simulations to scrutinize the performance of pipeline constructions.

In this work the focus is on phenomenological plasticity models which rely on the concept of a yield surface and a strain hardening law. The material under investigation in this paper (S690QL HSS) exhibits significant plastic anisotropy, and, consequently, the choice of an appropriate anisotropic yield function is of utmost importance. Conventionally, such material models are calibrated using material tests and the experimental effort usually scales with the complexity of the phenomenological yield function hampering the industrial application. The ultimate goal of this work is to reduce the amount of experimental effort to identify the plastic material behaviour of HSS whilst retaining sufficient accuracy to evaluate pipeline constructions through reliable simulations.

Mixed experimental-numerical techniques, also referred to as inverse methods, such as Finite Element Model Updating (FEMU) [1] and the Virtual Fields Method (VFM) [2] aim to reduce the amount of experimental work by extracting more information from a single experiment. Indeed, complex shaped specimens can generate complex deformation fields which contain more information enabling to simultaneously identify more parameters. Such alternative methods rely on full field information to identify material models. Rossi and Pierron [3] presented a general VFM-based procedure to extract the constitutive parameters of a plasticity model using 3D displacement fields. The method was validated using simulated displacement data. In practice, however, the method relies on in-situ X-ray tomography measurements along with Digital Volume Correlation software [4] to acquire the 3D displacement fields. Today, however, the latter techniques are not widely spread in experimental mechanics and therefore we opt to develop a FEMU approach for thick HSS. Fig. 1 schematically shows the FEMU procedure: the unknown material parameters in the finite element (FE) model are iteratively minimized. This is done using a certain cost function which expresses the discrepancy between the experimentally measured and the computed data. As a first step, this paper presents a FEMU method to identify the strain hardening behaviour of thick HSS at large plastic strains (i.e. beyond the point of maximum uniform strain). The impact of the boundary conditions (BC) in the FE model and the chosen cost function on the accuracy of the identified strain hardening behaviour is scrutinized.

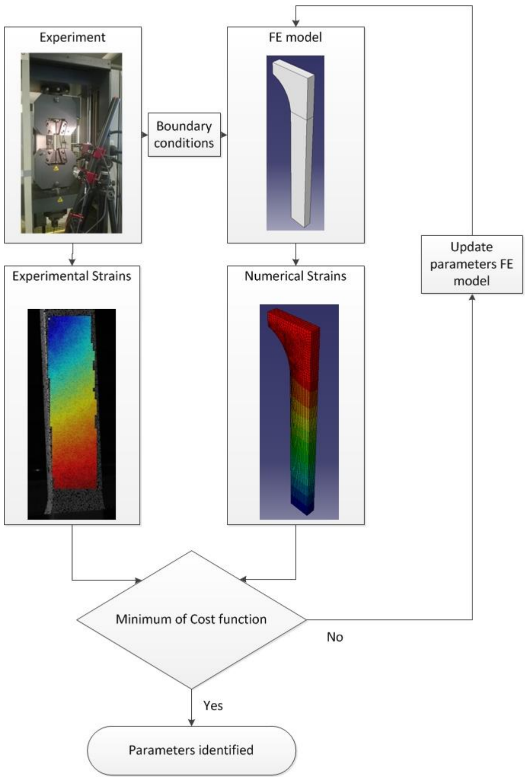

Figure 1 - Principle of FEMU

2. BOUNDARY CONDITIONS

The FEMU approach requires the development of a FE model which inherently implies that the BC are assumed to be known. The tensile test on a perforated specimen (see left panel of Fig.2) can be modelled using different BC. The experimentally measured force can be applied as a traction force resulting in a force-driven simulation. Alternatively, a displacement-driven simulation imposes experimentally measured displacements as a BC. Clearly, in practice the exact load or displacement distribution is not known and this can bias the identification of the unknown material parameters.
FEMU has been widely applied to identify the elasto-plastic material properties of sheet material [5-6]. Cooreman et al. [5] identified the pre-necking plastic material behaviour of sheet material and used the experimentally measured force as BC in the FE model while the surface strains were minimized using a cost function. Probing post-necking material behaviour, however, requires a FE model capable of dealing with a plastic instability. This directly implies that a force cannot be used as a BC due to numerical instability of the FE model. To cope with this problem, a displacement-driven simulation must be used to identify the post-necking hardening behaviour of sheet metal [6]. In the case of sheet metal, plane stress conditions can be assumed. Indeed, the through-thickness displacement is constant enabling to extract the correct BC from the displacements measured at the surface of the specimen. In this work, however, thick material is used and plane stress conditions are not valid. The surface displacements can be measured using DIC and applied as BC in the FE model thereby ignoring possible through-thickness heterogeneity with respect to the displacements. In this section, the influence of the BC on the accuracy of the FEMU procedure on thick material is numerically investigated. To this purpose, the tensile test on a perforated thick tensile specimen is simulated using Abaqus/Standard. The reference strain hardening behaviour used in the simulation is described by the Swift hardening law:

$$\sigma_y = K\left(\varepsilon_{eq}^{pl} + \varepsilon_0\right)^n \tag{1}$$

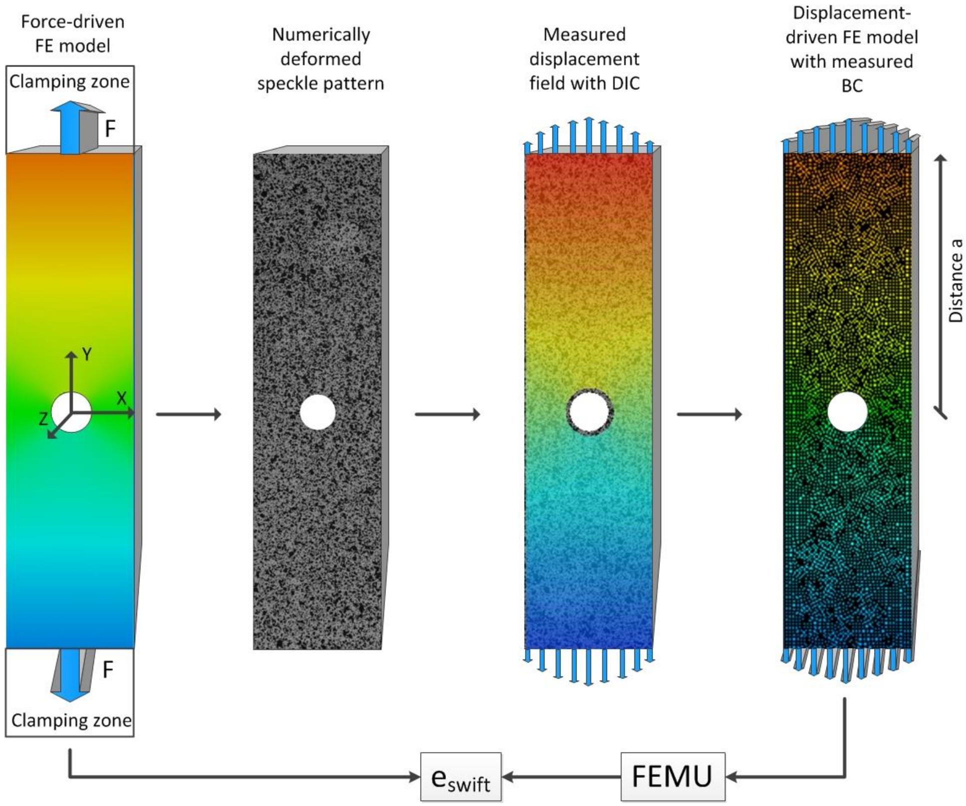

Figure 2 - Numerical procedure to study the impact of the boundary conditions on the identified hardening behaviour.

with K the deformation resistance, ε_0 the initial deformation, n the hardening exponent, ε_{eq}^{pl} the equivalent plastic strain and σ_y the initial yield stress. In order to have a realistic situation, the simulation was force-driven by applying a traction force as BC allowing through-thickness heterogeneity of the displacements. Next, the simulated displacement fields at the surface of the specimen are used to numerically deform a speckle pattern [7]. A 2D-DIC code [8] is then used to extract the displacement fields and the strain fields. Finally, the measured displacements are applied as BC in a displacement-driven simulation and employed in a FEMU approach to identify the hardening behaviour. It must be noted that in this section the FEMU approach relies on the minimization of the discrepancy of the measured and computed strains. This numerical approach, schematically shown in Fig. 2, excludes all experimental errors and allows studying the impact of the BC in a displacement-driven FEMU on the identified strain hardening behaviour. The accuracy of the identified strain hardening behaviour can be expressed as:

$$e_{swift} = \frac{1}{k}\sum_{i=1}^{k}\left|\frac{\sigma_{y,i}^{ref} - \sigma_i^{ID}}{\sigma_{y,i}^{ref}}\right| \tag{2}$$

with k, σ_y^{ref} and σ^{ID} a number of equidistant points in the stress-strain curve described by Eq.(1), the reference equivalent stress used in the force-driven simulation and the identified equivalent stress, respectively. DIC yields displacement components in the XY-coordinate system shown in Fig. 2. As such, it is possible to apply the displacement components in the X and Y-direction or solely in the Y-direction (tensile direction) as BC in the FE model. Fig. 3 shows the accuracy of the identified strain hardening behaviour e_{swift} as a function of the distance (*a*, see Fig. 2) from the centre of the perforated specimen to the position where the displacement is applied as a BC in the FE model.

It can be inferred from this figure that if the displacement component in the X-direction is ignored in the BC (dashed line in Fig. 3), the accuracy is lower than if both displacement components are used (dotted line). Additionally, it can be seen that the larger the distance a, the smaller the error on the identified hardening law.

The latter can be explained by the level of homogeneity of the displacement through the thickness of the specimen. The further away from the heterogeneous zone around the hole, the more homogeneous the displacement through the thickness of the specimen will be. Fig. 4 shows the through-thickness homogeneity $\partial_{disp}(x)$ at the first load step of the simulation. The through-thickness homogeneity $\partial_{disp}(x)$ is calculated as:

$$\partial_{disp}(x) = \left|\frac{v^{out}(x) - v^{in}(x)}{v^{out}(x)}\right| \tag{3}$$

with v^{out} and v^{in} the specimen's outer and inner displacement component along the tensile direction as a function of the X-coordinate. Finally, applying the BC sufficiently far away from the heterogeneous zone yields satisfying results. Fig. 3 shows that a distance a=80 mm yields an error in the identified hardening law of less than $e_{swift} = 1\%$. In practice, however, it can be difficult to simultaneously measure the displacement field in the heterogeneously deforming region and the BC far away from this zone.

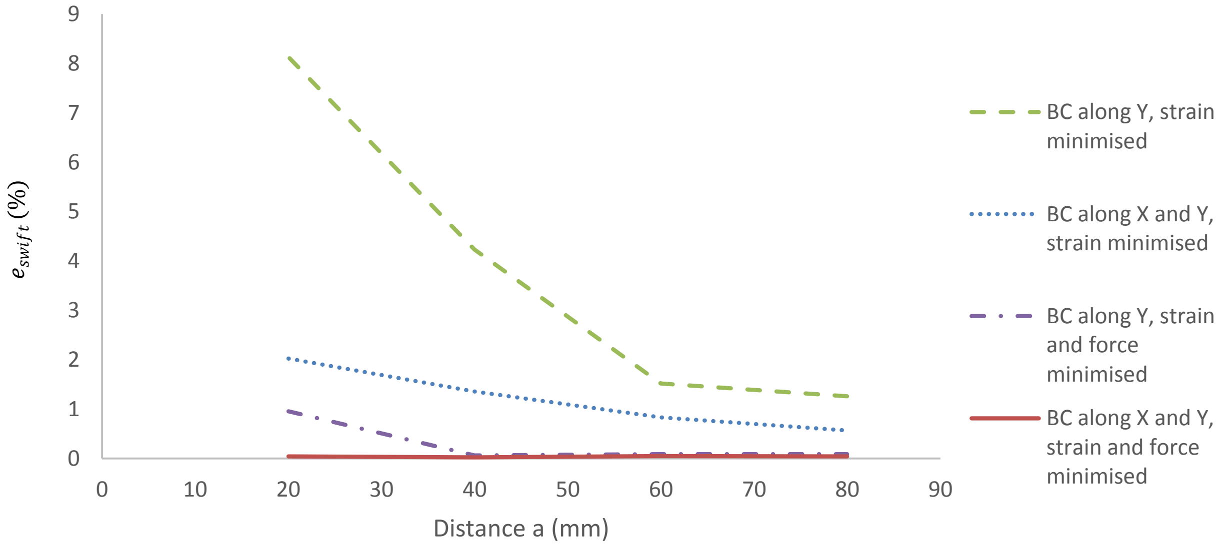

Figure 3 - Accuracy of the identified strain hardening behaviour as a function of the distance a

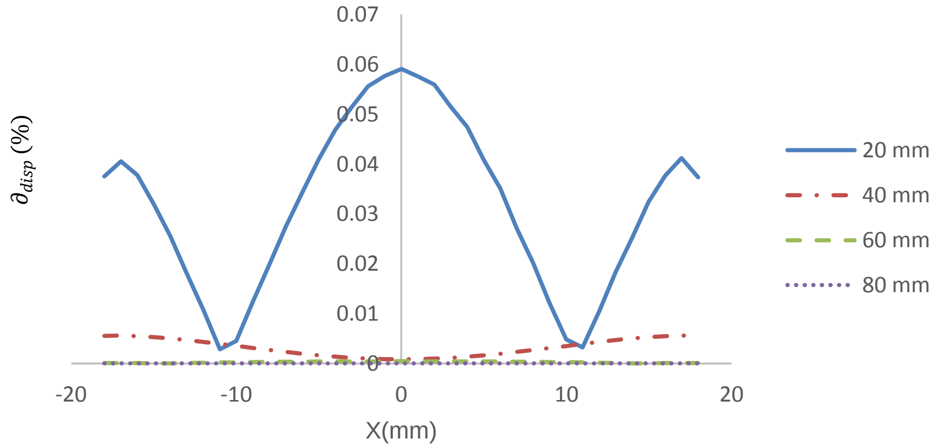

Figure 4 - Through-thickness homogeneity at load step 1 (208 kN)

3. COST FUNCTION

Instead of using only the discrepancy of computed and measured surface strains, also the tensile force can be taken into account. These two physical quantities have a different order of magnitude and need to be normalized so that they have the same weight in the cost function. The general cost function C(p) can be decomposed in two separate cost functions and reads as:

$$C(p) = C(p)_1 + C(p)_2 \tag{4}$$

with the cost function $C(p)_1$ formed by the numerical and experimental strain components ε_{xx} , ε_{yy} and ε_{xy} normalised by their root mean square (RMS) of the region of interest:

$$C(p)_1 = \sum_{i=1}^{m} \sum_{j=1}^{n_i} \left[\left(\frac{\varepsilon_{xx,ij}^{exp} - \varepsilon_{xx,ij}^{num}}{\varepsilon_{xx,RMS,i}^{exp}} \right)^2 + \left(\frac{\varepsilon_{yy,ij}^{exp} - \varepsilon_{yy,ij}^{num}}{\varepsilon_{yy,RMS,i}^{exp}} \right)^2 + \left(\frac{\varepsilon_{xy,ij}^{exp} - \varepsilon_{xy,ij}^{num}}{\varepsilon_{xy,RMS,i}^{exp}} \right)^2 \right] \tag{5}$$

and the cost function $C(p)_2$ consists of the experimentally measured and numerically computed tensile force normalized by the experimental value:

$$C(p)_2 = \sum_{i=1}^{m} \left[n_i \times \left(\frac{F_i^{exp} - F_i^{num}}{F_i^{exp}} \right)^2 \right] \tag{6}$$

with m the number of load steps and n_i the number of data points at load step i. It can be seen from Fig. 3 (red solid line) that by including the force in the cost function (Eq.(4)) the dependency on the through-thickness homogeneity decreases dramatically. Even if only the displacement components in the tensile direction are used to define the BC (dotted-dashed line) the accuracy is significantly improved. These results suggest that the tensile force cannot be ignored in constructing the cost function.

4. EXPERIMENT

The presented FEMU approach with the derived optimal BC has been applied on a 10 mm thick and 36 mm wide S690QL HSS perforated specimen. The tensile test is conducted with a constant cross head speed (1mm/min) on a tensile bench with a load capacity of 250kN equipped with wedge grips. The displacement components along the X and the Y-direction have been extracted from a 3D-DIC measurement and applied on a displacement-driven FE model used in the FEMU method. A swift hardening law has been identified while the strains and forces were minimized using cost function Eq.(4). Fig. 5 shows the identified hardening behaviour (dashed line) along with the hardening behaviour obtained from a standard tensile test (solid line).

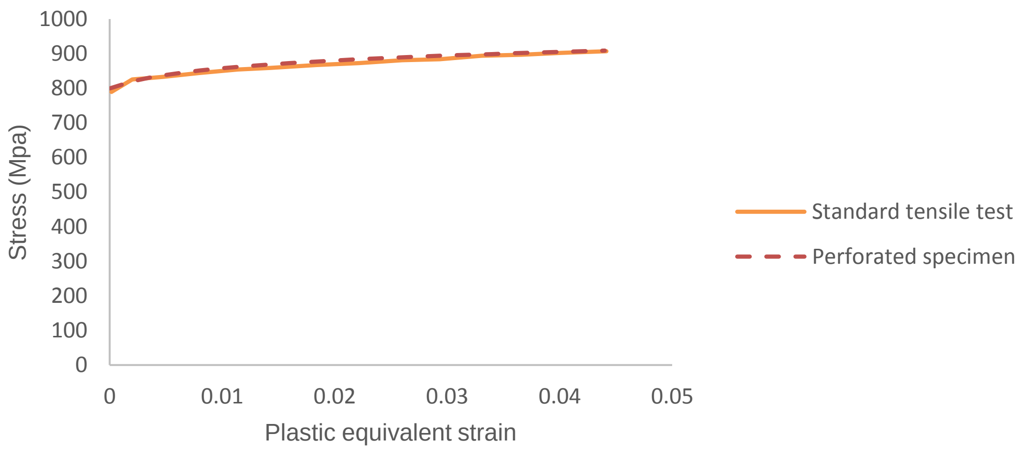

Figure 5 - Identified swift law for S690QL

5. CONCLUSION

The BC for FEMU on thick high strength steels are numerically investigated. If a displacement-driven FE model is used, the BC need to be applied in X and Y direction and the cost function needs to be based on the discrepancy of strains and forces to have optimal results. The established optimal BC and cost function are used to identify the strain hardening behaviour of a 10 mm thick S690QL HSS specimen. The results of the FEMU procedure on a perforated tensile specimen were in good agreement with those obtained with a standard tensile test.

6. REFERENCES

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